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1319652

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(54) IMPROVEMENTS IN OR RELATING TO ELECTROSTATIC LOUDSPEAKERS AND SYSTEMS EMPLOYING SAME

(71) I, HAROLD NORMAN BEVERIDGE, a citizen of the United States of America, of 1616 Franceschi Road, Santa Barbara, State of California, United States of America, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to electrostatic loudspeakers.

The invention provides an electrostatic loudspeaker comprising a diaphragm which has at least one conductive face and which is mounted under tension, and an adjacent driver plate which comprises a conductive sheet and, on the side thereof facing the diaphragm, a dielectric portion which is substantially thicker than an air gap which separates the dielectric portion and the diaphragm when the latter is in a neutral position, the relative permittivity of the dielectric portion being greater than 30 at audible frequencies.

The use of a driver plate which is relatively thick compared to the air gap and is of high relative permittivity permits the use of very high voltages, while concentrating the effective electric field to the air gap. The dielectric portion has a volume resistivity in the range from 10^8 to 10^{11} ohm centimetres in order to provide rapid leakage of charge from the inner face of the driver plate, should the diaphragm accidentally touch it, as when a transient occurs. It is the purpose of the tension mounting of the diaphragm ordinarily to prevent such detrimental contact—but when large transient signals occur—as when switching FM channels—the signal may be so large as to cause the diaphragm to touch the driver plate and the low resistance here provided is found to be effective to conduct off rapidly the charge to permit the diaphragm to resume proper operation.

The dielectric portion is preferably more than three times as thick as the adjacent air gap, even hough the air gap may be smaller than the preferred order of ¼ inch. A relatively thick dielectric portion on the inner surface of the driver plate avoids power arcs while permitting a relatively high energy output per unit diaphragm area, judged against ordinary electrostatic speakers. The loudspeaker can present a capacitance of for example 750 to 1000 pf per square foot of diaphragm area and total capcitance ranging up to 2000 pf and above, with virtually no resistive impedance in the operative frequency range.

The dielectric portion may be moulded of a dielectric material in which is dispersed a substance of relatively much higher relative permittivity, for example greater than 500. A further additive is useful to lower the volume resistivity of the electrode to preferably about 10^{10} ohm centimetres.

The loudspeaker is preferably of balanced construction in which two driver plates, each as aforesaid, are provided, one on each side of the diaphragm.

The invention includes within its scope a loudspeaker arrangement including a loudspeaker as described, means for providing a polarizing voltage between the or each driver plate and an amplifier for audio frequency signals, connected to feed the loudspeaker. The invention also provides, as described hereinafter, a loudspeaker system including such an arrangement and an acoustic lens and enclosure for the loudspeaker.

In the drawings:

Figure 1 is a cross-sectional view of a full audio range electrostatic speaker according to the invention including schematically an amplifier system;

Figure 2 is a partially broken way perspective view of a preferred electrode plate;

Figure 3 is a partial cross-sectional view of the speaker of Figures 1 and 2;

Figure 4 is a cross-sectional view showing

[*Price 25p*]

an edge member being formed on the electrode plate of Figure 2;

Figure 5 is a cross-sectional view of a balanced electrostatic transducer being formed from two electrodes in accordance with Figure 4;

Figure 6 is a schematic utilized to illustrate the difficulty of using conventional amplifier circuitry to drive a capacitive load;

Figure 7 is a simplified schematic of an amplifier for use with the elecrostatic loudspeaker illustrated in Figures 1 to 5;

Figure 8 is a block diagram of an entire loudspeaker system embodying the invention; and

Figure 9 is a detailed schematic of electronic components connected to a balanced electrostatic loudspeaker.

Referring to Figure 1 there is shown an embodiment of a full range electrostatic loudspeaker in accordance with the invention. The basic components comprise an electrostatic transducer 10 including a large flexible tensioned diaphragm 12 which comprises polyester film, sold under the name "MYLAR" (Registered Trade Mark), coated on each broad face with metal, for example vacuum deposited aluminium, a pair of rigid, planar, driver plates 14 and 16, an enclosure 18 for the transducer 10, an outlet passage in the form of a lens 20, and an amplifier 22 including a feedback circuit 23, connected to feed the transducer.

The electrostatic transducer 10 extends across one third of the full width W of the enclosure 18, with a width W_d of 13 inches and a length (normal to the Figure) of 23 inches.

The electrostatic transducer of this embodiment is of the balanced type and the flexible diaphragm 12 is held in taut condition between the two apertured plates 14, 16.

The forward plate 16 is disposed immediately adjacent the inlet 20_i of a lens structure 20 composed of walls $20_1, 20_2 \ldots 20_{19}$ which are straight in the direction normal to the Figure but are spaced apart and curved in accordance with a special pattern in the one plane (here in the plane of the Figure but in normal use horizontally disposed) to define a series of adjacent channels which provide a narrow throat for helping to lower the resonant frequency of the loudspeaker and also serving to disperse the high frequencies through a large angle α. The construction of the loudspeaker as far as the transducer and lens are concerned, forms the subject of our co-pending application for Letters Patent No. 28571/70 (Serial No. 1,319.651) from which the present application is divided.

Referring to Figure 5, the diaphragm 12 is conductive on both sides. With such diaphragms the use of a *bare* conductive fixed driver plate would lead to power arcs that could destroy the diaphragm. However, the driver plates are, in accordance with the invention, provided on the faces nearer the diaphragm with dielectric portions which are substantially thicker, i.e. about 3 or more times greater in thickness than, the thickness of the air gap between each of the said portions and the diaphragm when the latter is in its neutral position.

Each dielectric portion is preferably a moulded dielectric body in which a substance of substantially higher relative permittivity (preferably greater than 500) has been dispersed, a provision which readily permits the obtained of a mean relative permittivity which is greater than 30.

The body material may be selected from various mouldable dielectric substances that are available; good results are achieved using epoxy, of relative permittivity below ten, for example from four to six. To this is added, before moulding, a dispersion of a substance of much higher permittivity (such as barium titanate of which the relative permittivity is from 1000 to 1500). Advantageously, also a dispersion of a conductive substance (such as carbon) is added, having a lower volume resistivity than the body material to achieve a volume resistivity in the range of 10^8 to 10^{11} ohm centimetres.

The properties of the resulting driver plate are not linear. In particular its permittivity drops at high frequencies to approximately two-thirds of its low frequency value.

The permittivity of the dielectric portion preferably remains high enough in the frequency range of several hundred kilocycles per second to permit the use of that order of frequency for determining the diaphragm's movement and velocity for negative feedback purposes, discussed further below.

In a suitable procedure for preparing the dielectric portions, barium titanate and carbon powders are mixed together with a suitably-proportioned mass of epoxy in the liquid state, prior to reaction. The mixture is then cast into a mould in the desired form and cured.

Referring to Figures 4 and 5, the triangles in the cross-sections suggest the uniform dispersion of fine barium titanate particles and the circles suggest the uniform dispersion of carbon particles. Employing substantially equal weights of barium titanate and epoxy, and carbon to approxmitely 5 per cent of the weight of the epoxy, produces a suitable dielectric of which the relative permittivity is between 30 and 40 and of which the volume resistivity is approximately 10^{10} ohm centimetres.

Slots which are moulded integrally into the electrode plate 14 have length L of 2 inches, a width S_1 of 1 1/16 inch on the side that is to face the diaphragm and a width S_2 of 1/8 inch on the side that faces away from the diaphragm. Each land between the slots converges in complementary manner from a

width of 3/16 inch to a width of 1/8 inch. The thickness t is about 1/4 inch.

The inlet surface of the electrode is cast precisely planar and smooth. The outlet surface is smooth and after formation is coated with a conductive layer 14*c*, Figure 5, e.g. an epoxy containing a dispersion of fine silver-coated particles.

After its formation the plate 14*a* is appropriately jigged, see Figure 4, and an edge member 14*b* is moulded integrally therewith. A planar casting plate 38, e.g. of plate glass forms the inside edge surface 14*c* of the edge member 14*b*. A removable spacer 40 of uniform thickness approximating the thickness A_g of the desired air gap between the plate and the diaphragm rests upon the casting plate 38 and directly supports the inlet surface of the electrode during this operation. Jig members 42 and 44 form the outline of the edge member 14*b*. The edge members may be formed of the same material as the dielectric body of the electrode plate, however omitting the additives.

Referring to Figure 5, two such plates 14 and 16 are brought together, inner surfaces directed toward each other and frame surfaces 14*c* aligned. The thin flexible conductive diaphragm 12 is disposed between the plates. Tension T (of several thousand p.s.i.) is applied to the diaphragm, whereupon the plates 14 and 16 are permanently clamped to the diaphragms, e.g. by means of adhesive applied to mating surfaces 14*c* or by bolting the two electrodes together. The thus formed electrostatic driver is then ready for mounting within the speaker enclosure.

For full range electrostatic speakers the polarizing voltage across the fixed electrodes may range between about 2 to 8 kilovolts. The air gap between the diaphragm (in mid-position) and each fixed driver plate ranges between 1/20 to 1/10 inch. The thickness of each plate is preferably about 1/4 inch.

The signal voltage is divided across the electrode thickness and the air gap. Little signal voltage is lost across a driver plate, the signal voltage being concentrated in the air gap by the electode of high dielectric constant.

In a particular example the polarizing voltage together with the audio peak is established at 6,000 volts between diaphragm and electrode and the air gap A_g is .070 inch.

The speaker just described imposes severe operating requirements upon the associated amplifier system. To obtain the requisite levels of audio output without requiring an unduly large diaphragm, the audio drive voltage must be quite high, a peak drive potential of 4,000 volts being employed. The speaker impedance is almost entirely capacitive (3,000 to 6,000 pf.) and peak currents in excess of 300 ma. are sometimes required, implying a peak output requirement of many hundreds of volt amperes. The output transformers generally used to drive conventional moving-coil speakers (which have a relatively low and essentially resistive impedance, e.g. eight ohms) are ill suited to the demands of this electrostatic speaker. Transformers having the requisite output are cumbersome, expensive, and present resonance problems when used to drive a capacitive load.

A simple schematic is presented in Figure 6 to illustrate the difficulties of driving an electrostatic speaker directly from the output of a conventional resistance-coupled amplifier. An audio input signal 52 is applied to amplifying tube 54 and a plate supply voltage of +4,000 volts is applied to terminal 56. If capacitive load 60 is 3,000 pf. its impedance at 10 KHz is about 5,500 ohms. For the loss in response at that frequency to be limited to three db., the plate resistor 58 can be no larger than 5,500 ohms. The plate supply would then have to furnish about 375 ma. or 1,500 watts to terminal 56. This is, of course, highly inefficient and impractical.

The inventor has devised a low-impedance amplifier circuit that produces the required output with efficiency, stability, linearity, and a relatively low-level input. A simplified schematic of this circuit is shown in Figure 7. An audio input signal 52 of about ten-volt amplitude is applied to the grid of pentode T3. (Like elements are designated with identical reference numerals throughout all the figures.) The terminal 56 plate supply of pentode T2 is +4,000 volts. Capacitor 60, representing the load presented by the electrostatic speaker, has a value of 3,000 pf. A −100 volt potential is applied to 10 K cathode resistor 62 at terminal 64. The output current to the load 60 may have a peak value of over 300 ma. in either direction.

In the quiescent no-input state, pentode T3 develops a well-defined plate current of slightly over 1 ma. through the 2M feedback resistor 66. About 2040 volts is developed over resistor 66 so that point B settles at a quiescent voltage of about +2,000 volts, while point A settles at about −40 volts. About 6 ma. flows from terminal 56 through pentode T2, 7 K resistor 68 and pentode T1.

Point B is held stable at +2,000 volts by a feedback resistor 66. Should it tend to rise to a higher voltage, the voltage increase would be applied through resistor 66 to the grid of pentode T1, causing T1 to conduct more heavily and thus lowering the output voltage at point B. Conversely, were the voltage at point B to tend to fall to a lower value, the drop would also be fed back through resistor 66, reducing the conduction through pentode T1 and increasing the plate voltage of T1 and decreasing the voltage between grid and cathode of pentode T2 (the grid of T2 is directly coupled to the plate of T1). The

resulting increase in conduction through T2 causes the voltage at point B to rise restoring the equilibrium output value of +2,000 volts.

The small-signal output impedance of the circuit is extremely low. Assume, for example, that pentodes T1 and T2 each have a transconductance of 1000 microhms and that a one volt incremental voltage is applied to point B. This incremental voltage is fed back through resistor 66 to the grid of T1, resulting in a one ma. increase in the plate current of T1 and a seven volt increase in the drop across resistor 68. The resulting seven volt increase in the grid bias of T2 reduces the cathode current of T2 by seven ma. The total change in current at point B (as seen by the load) is thus the increase in the plate current of T1 plus the decrease in the cathode current of T2 (1 ma.+7 ma.=8 ma.). The small-signal output impedance of the amplifier is therefore only 1 volt/8 ma.=125 ohms.

Only a few tens of volts of drive are required from the plate of pentode T3 which, in driving point A, closely approximates a very linear constant current generator. The large unbypassed cathode resistor 62 ensures that the effective output impedance of the T3 stage is relatively high. (The effective resistance looking into the plate of T3 can be as high as 1 M.). Series-connected pentodes T1 and T2 function essentially as class B amplifiers, but the linearity of their operation is greatly increased by the 40 to 50 db. of negative feedback provided by resistor 66. Further linearity improvement can be achieved by customary feedback from point B to 52.

For large signal inputs, the amplifier can furnish very high peak currents, both positive and negative, to load 60. When pentode T2 conducts, the output current is limited only by the current capacity of T2 at low or zero bias, and peak currents of many hundreds of ma. can be furnished to the load.

When pentode T1 conducts, the output current is, in the first instance, limited by the 7 K resistor 68. However, by shunting a 100 volt Zener diode 70 across the resistor 68, the voltage drop can be limited to 100 volts and the current which T1 can supply to the load can then, for all practical purposes, be limited only by the current capacity of pentode T1 rather than by resistor 68.

A block diagram showing the entire electronic section of the system is presented in Figure 8. This block diagram incorporates amplifier elements similar to those shown in Figure 7 and in addition shows the audio feedback system used to damp the low frequency resonance of the system.

An audio input signal 52 is applied to input amplifier 72, a high-impedance, constant current stage or set of stages (which may even be solid state) serving the function of pentode T3 in Figure 7 and also serving to combine the audio input 52 with a feedback signal on line 73. Active devices 74 and 76, which occupy roles similar to those of pentodes T1 and T2 respectively, (but of course need not necessarily be pentodes) are connected in series between a high voltage source at terminal 56 and ground. The diaphragm of electrostatic transducer 80 is electrically connected to Point B, the junction of active devices 74 and 76, as is feedback resistor 66.

It is realized that damping of the low frequency resonance peak is desired. To a certain degree this is possible by viscous damping, e.g. using glass wool disposed immediately adjacent to the back of the transducer as suggested in dotted lines at 19*a* in Figure 1. Electronically this same damping is well achieved by feedback system 82. A signal generator 84 applies a 260 Kc/s signal to the diaphragm. This signal induces corresponding signals at electrodes 86 and 88 of electrostatic transducer 80. The amplitude of each of these signals varies with the distance of the diaphragm from the electrode; the closer the diaphragm, the stronger the signal. The induced signals on the two electrodes are detected and summed at diaphragm displacement detector 87. Successful operation is made possible by the fact that with the dielectric electrode made as described above, a substantial K (believed to be greater than about 15) exists at the frequency of the 260 Kc/s signal.

The resulting signal, centred around a zero voltage and ranging positive or negative depending upon the direction of diaphragm displacement from the centre position, is proportional to diaphragm displacement and is in quadrature with the transducer *drive* voltage at the resonant frequency. Diaphragm excusion should be inversely proportional to the frequency squared (i.e. displacement decreases 12 db. for each octave of frequency increase). The output of diaphragm displacement detector 87 is applied to differentiator 89, which generates a signal advanced in phase by 90° (and thus approximately in phase with the drive voltage). The amplitude of this differentiated signal is inversely proportional to frequency and so decreases 6 dm. for each octave of frequency increase.

The differentiator output signal is applied to feedback amplifier 90 which introduces a further 180° phase shift in the signal. The output from the feedback amplifier is returned through line 73 to constant current generator 72 and there summed with audio input signal 52. (The feedback system 82 is designed so that the feedback signal is significant only from about 20 Hz to about 200 Hz; its phase at those frequencies is such as to oppose the drive voltage.) To produce constant sound energy throughout the frequency range of the system (with constant drive amplitude) the system response curve should drop about 6 db per octave.

A detailed schematic drawing is shown in Figure 9 of those system components represented in block form in Figure 8. This practical circuit illustrates on implementation of the electronic portions of the electrostatic speaker system. Obviously an equivalent circuit employing solid-state elements is possible. In certain embodiments two amplifiers of identical construction are employed, one connected to the diaphragm and the other to the fixed electrodes, with a 180° phase shift between the two. This arrangement is generally suggested in Figure 1. For a given amount of audio signal a considerably more powerful output is obtained, relative to a one-amplifier embodiment.

WHAT I CLAIM IS:—

1. An electrostatic loudspeaker comprising a diaphragm which has at least one conductive face and which is mounted under tension, and an adjacent driver plate which comprises a conductive sheet and, on the side thereof facing the diaphragm, a dielectric portion which is substantially thicker than an air gap which separates the dielectric portion and the diaphragm when the latter is in a neutral position, the relative permittivity of the dielectric portion being greater than 30 at audible frequencies.

2. An electrostatic loudspeaker according to claim 1 in which the dielectric portion is a dielectric body that contains a dispersion of dielectric material of which the relative permittivity is much greater than that of the material of the body.

3. An electrostatic loudspeaker according to claim 2 in which the relative permittivity of the dispersed material is greater than 500 at audible frequencies.

4. An electrostatic loudspeaker according to any preceding claim in which the dielectric portion has a volumetric resistivity in the range from 10^8 to 10^{11} ohm centimetres.

5. An electrostatic loudspeaker according to any preceding claim, being of balanced construction in which two driver plates, each as aforesaid, are provided, one on each side of the diaphragm.

6. A loudspeaker arrangement comprising an electrostatic loudspeaker according to any preceding claim, means for providing a polarizing voltage between the diaphragm and the or each driver plate and an amplifier for audio frequency signals, connected to feed the loudspeaker.

7. A loudspeaker arrangement according to claim 6 in which the amplifier comprises first and second active amplifier devices in series, an output terminal, which is connected between the active amplifier devices, and an active device constituted by a constant current generator which is connected to receive and amplify an audio signal, the output of the constant current generator being connected to an input of the first active amplifier device, the said output terminal being connected to the output of the constant current generator and the output of the first active amplifier device being coupled to an input of the second active amplifier device.

8. A loudspeaker arrangement according to claim 7 in which a signal generator is arranged to provide a signal, of relatively high frequency with respect to the audio range, to the diaphragm, a circuit adapted to sense the high frequency signal as modulated by movement of the diaphragm and a feedback circuit for coupling the modulated signal to the constant current generator in addition to the said audio signal.

9. A loudspeaker arrangement according to claim 8 in which the input of the second active amplifier device is directly connected across the resistive load of the first active amplifier device.

10. A loudspeaker arrangement according to claim 6 and any of claims 7 to 9, in which the output terminal of the said amplifier is connected to said diaphragm, the output terminal of a second similar amplifier is connected to both driver plates and a phase inverter means is provided to invert the audio input of one of said amplifiers with respect to the other.

11. A loudspeaker arrangement according to any of claims 7 to 10, in which, for the or each amplifier, the active amplifier devices and the constant current generator comprise respectively first, second and third thermionic valves each having at least a cathode, anode and a control grid, and the anode of the first valve is connected through a resistor to the amplifier's output terminal and the cathode of the second valve, the cathode of the first valve and the anode of the second valve are connected across a DC potential in excess of one thousand volts, the anode of the second valve being positive, the anode of the first valve is connected to the grid of the second valve, and the grid of the first valve is connected to the anode of the third valve and through a resistive feedback path to the output terminal.

12. A loudspeaker arrangement according to claim 11 in which means is connected between the output terminal and the anode of the first valve, across said resistor to prevent said resistor from limiting the amount of current which said first valve can supply to said output terminal.

13. A loudspeaker system comprising a loudspeaker arrangement as claimed in any of claims 6 to 12, an acoustic lens which is disposed to disperse sound waves emitted from one side of the loudspeaker, the lens comprising a series of laterally adjacent channels which together narrow to a throat region and curve apart at their outlets and an enclosure which is adapted to contain

backwardly moving sound waves emitted from the other side of the loudspeaker.

14. An electrostatic loudspeaker substantially as hereinbefore described with reference to and as illustrated in Figures 1 to 5 of the accompanying drawings.

15. A loudspeaker system substantially as hereinbefore described with reference to and as illustrated in any of Figures 1 and 7 to 9 of the accompanying drawings.

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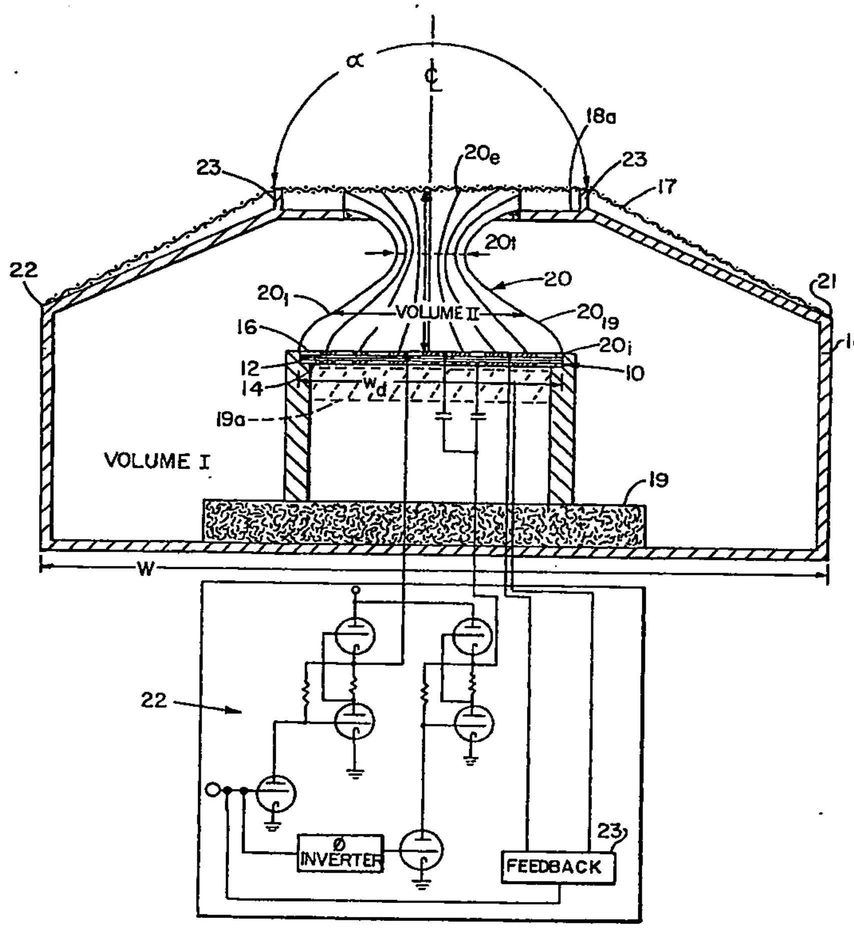
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FIG. 1

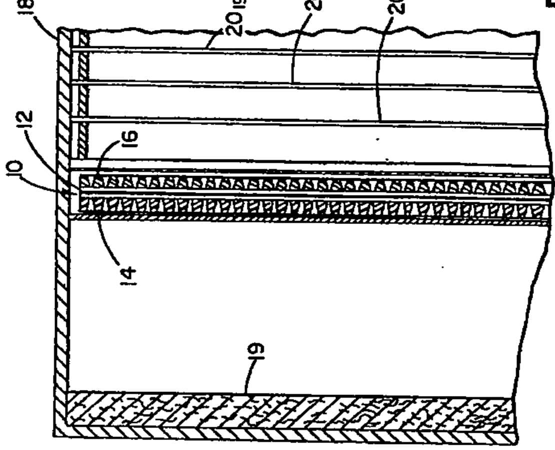

FIG. 3

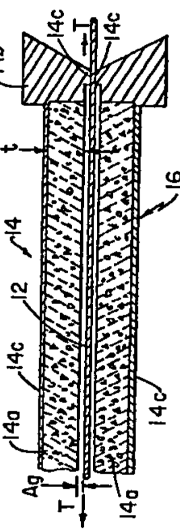

FIG. 5

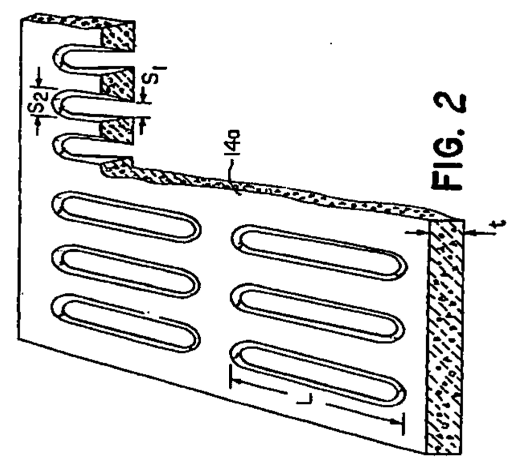

FIG. 2

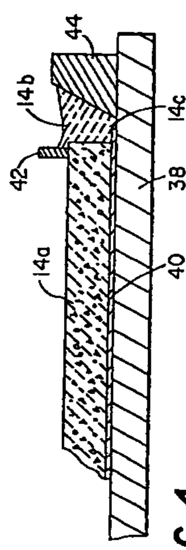

FIG. 4

1319652 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

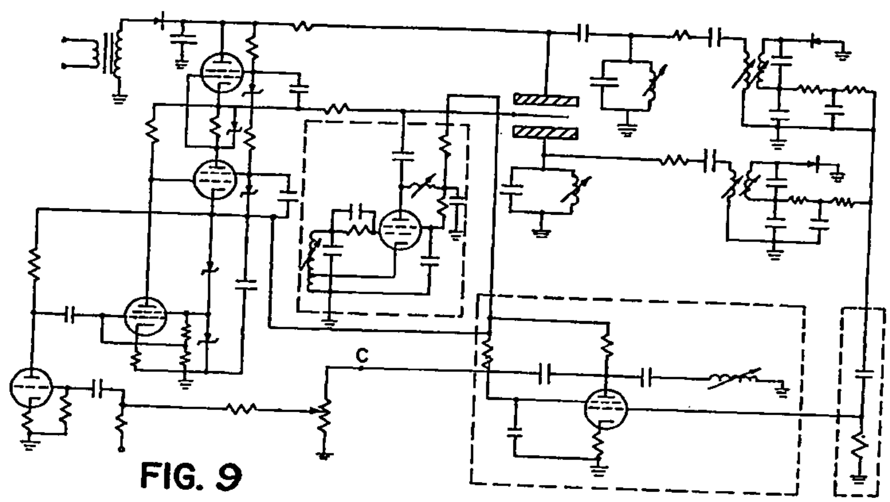

FIG. 9

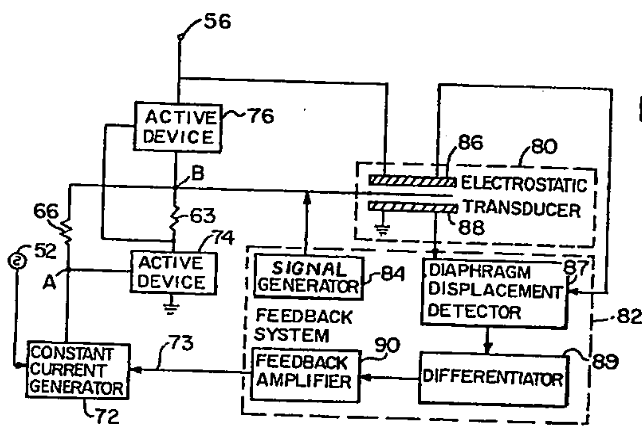

FIG. 8

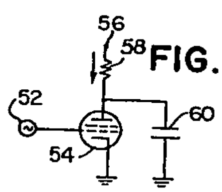

FIG. 6

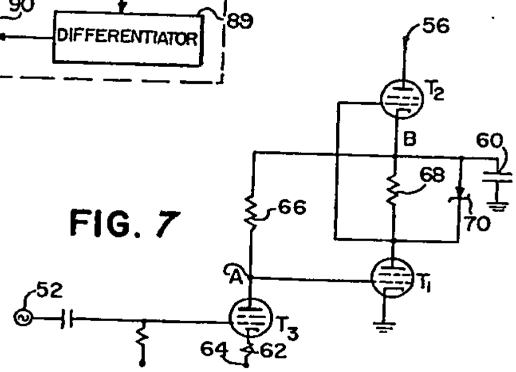

FIG. 7